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Title: High Fidelity Multi-physics Modeling of the Versatile Test Reactor (VTR)

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High Fidelity Multi-physics Modeling of the Versatile Test Reactor (VTR)

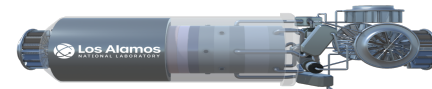
Jack Galloway, NEN-5

06/30/2021

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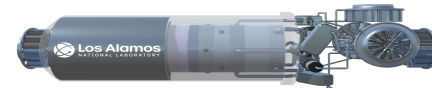
Outline



- What is the Versatile Test Reactor (VTR)?
- LANL VTR Responsibilities & Associated Collaborators
 - Neutronic and system confirmatory analyses
 - Note: System analyses not presented due to time constraints
 - Extended Length Test Assembly – Cartridge Lead (ELTA-CL) design
- MCNP Neutronic Analyses Methodology, Results, & Conclusions
- ELTA-CL Purpose & Design Process



What is the VTR?



- The VTR is a sodium fast reactor (SFR) providing a very high fast flux irradiation capability
 - Ternary metal fuel (U-Pu-Zr) fuel rod, liquid sodium coolant
 - Numerous experimental locations within the core
- Why the VTR?
 - New materials and reactor concept testbed
 - VTR is intended to shorten the development and approval horizon for materials



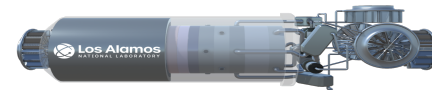
LANL Responsibilities for the VTR:

- Neutronic and system supporting design analyses
 - NEN-5 VTR confirmatory analyses using independent methods
 - The system response analyses are impressive, but not included here
- ELTA-CL (lead based experimental cartridge) design











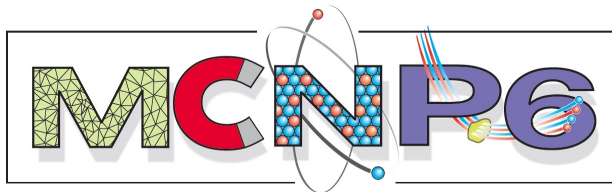
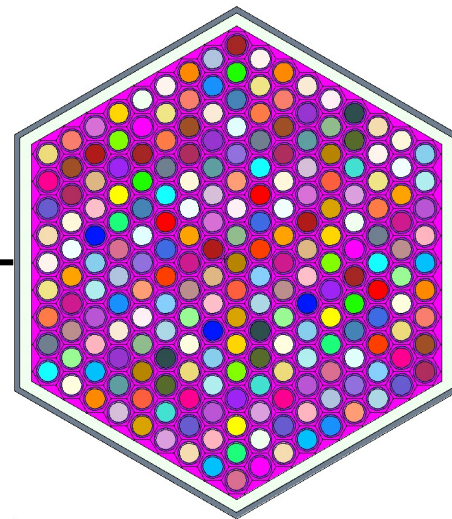
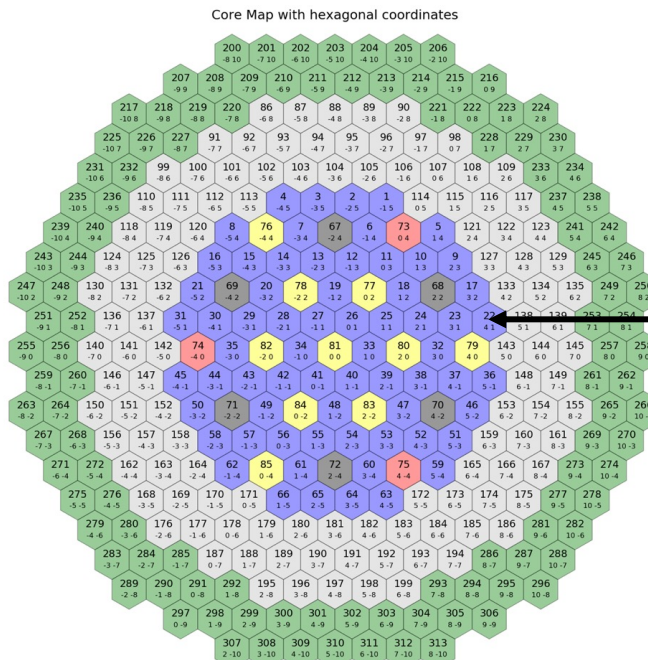
NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses



- VTR design (right) has primarily been conducted at ANL

- Radial view of the VTR layout

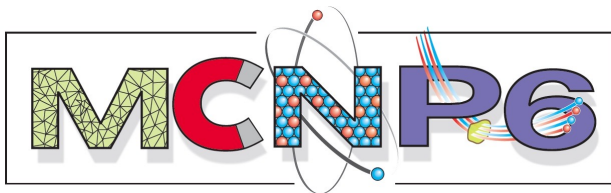
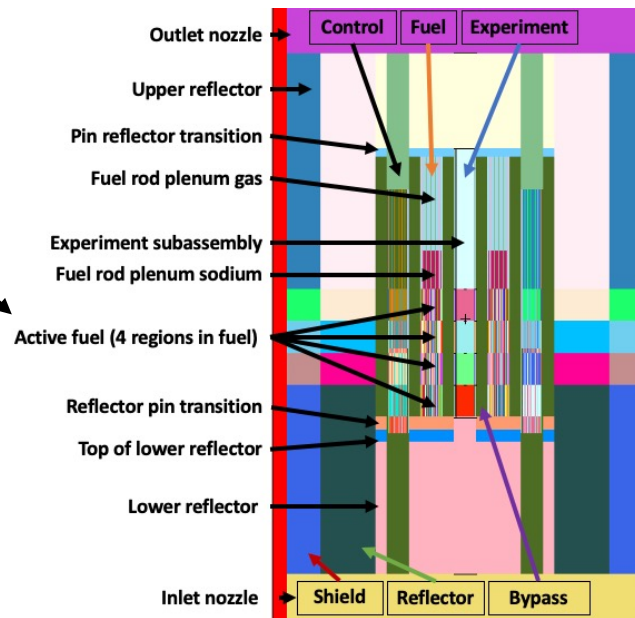
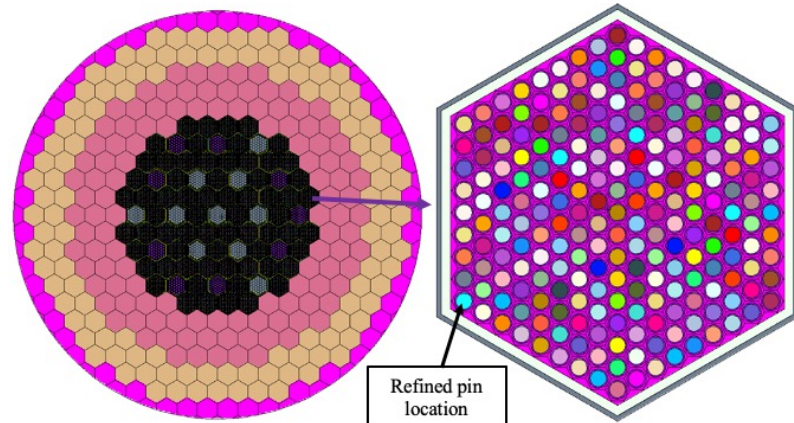
- U-Pu-Zr fuel assemblies 
- Control rod assemblies 
- Safety rod assemblies 
- Experiment assemblies 
- Reflector assemblies 
- Shield assemblies 





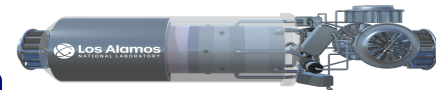
NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses

- MCNP model axial fidelity
 - Highly detailed in the active core
 - 4 axial regions in the active fuel
 - One refined fuel pin per assembly
 - Characterize:
 - Reactivity and kinetic parameters
 - Neutron flux & power
 - Photon flux & power
 - Control rod worth
 - Safety rod worth

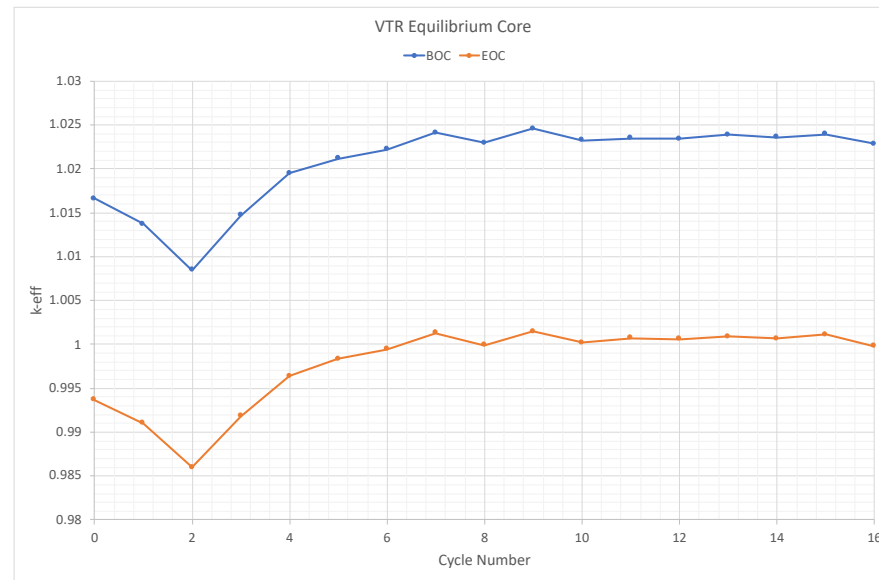
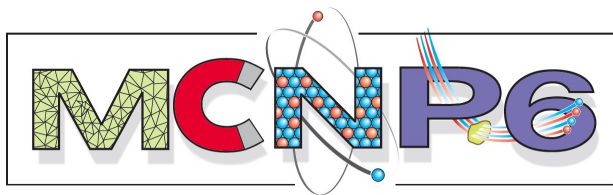




NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses, Equilibrium Core Analysis

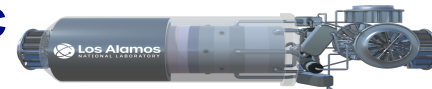


- Equilibrium core, what is it?
 - ~60,000 depletion zones
 - Equilibrium essentially achieved at cycle 10
- Homogenization versus discrete modeling
 - Benefits and drawbacks
- High-fidelity MCNP model allows in-depth physics analysis

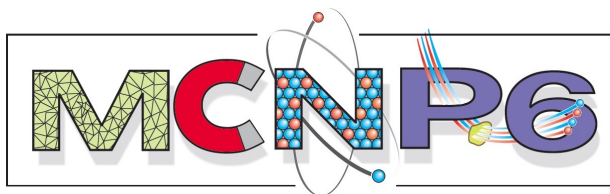
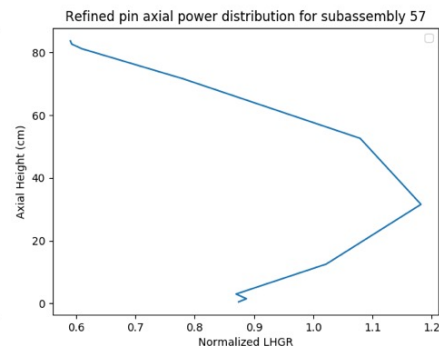
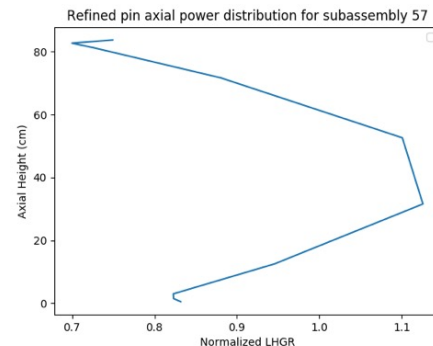
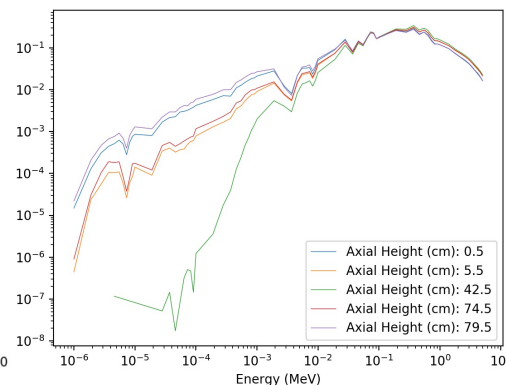
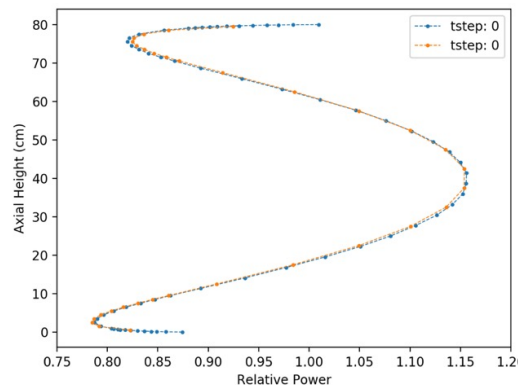




NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses



- High-fidelity MCNP model benefit
 - Pin-cell model versus whole core
 - Puzzling (unexpected) power peaking
 - Cause and implications?
- New physical understanding garnered!
 - Cause: Slowing of fast neutrons towards the top of the rod (middle)
 - In reactor occurrence: Yes, but only sometimes (bottom)
- Particular importance for fuel failure mechanisms

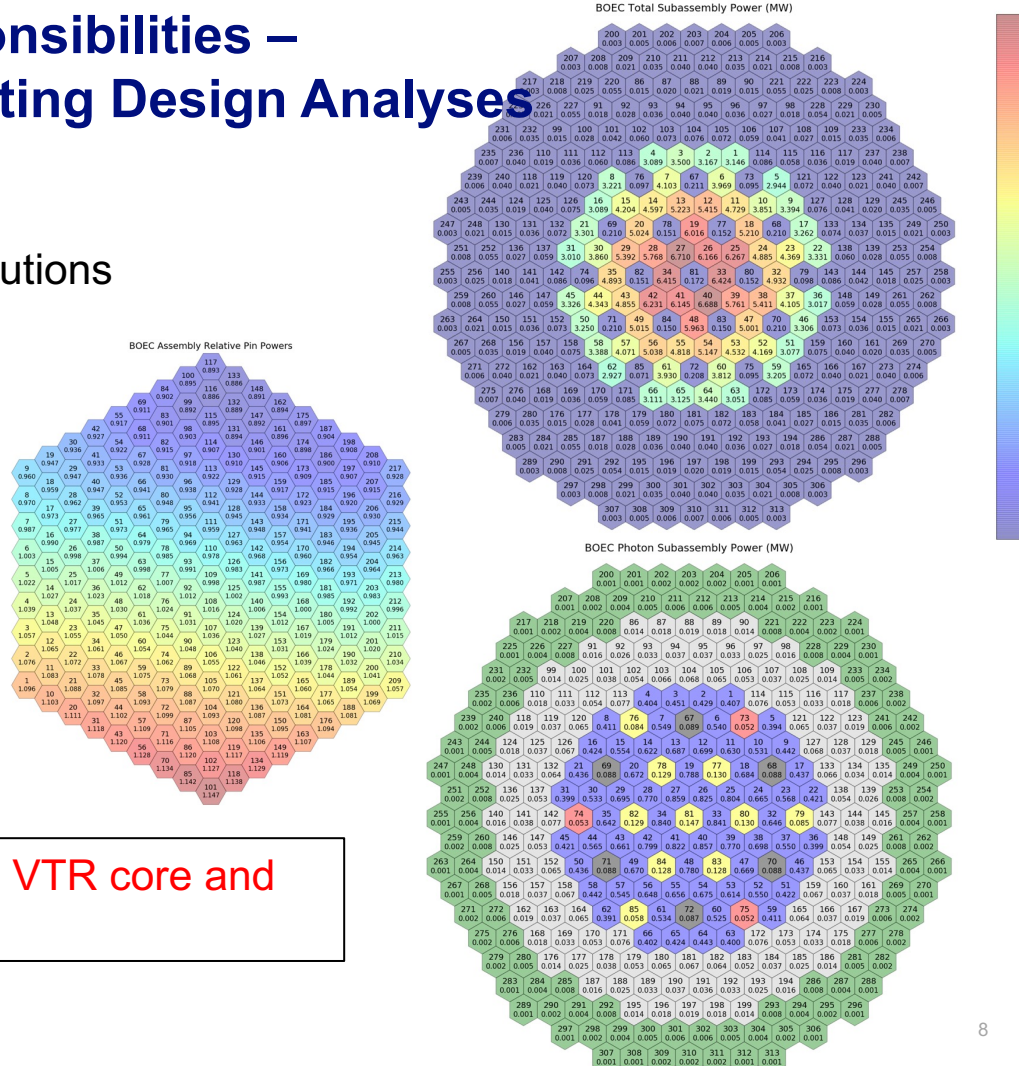




NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses

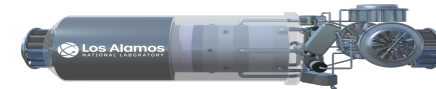
- Power distributions
 - Total power, neutron and photon contributions
 - Integral pin power peaking
 - Thermal limits implications
- Flux distributions
 - Neutrons and photons
 - Flux values at each location proved invaluable during ELTA-CL design iterations
- Further design analyses
 - Cartridge implications

Our work confirms the general design of the VTR core and highlights areas of increased importance

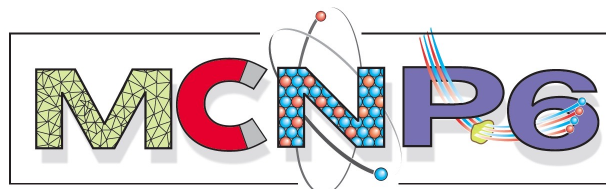
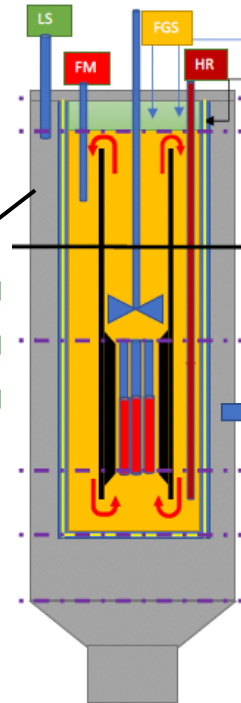
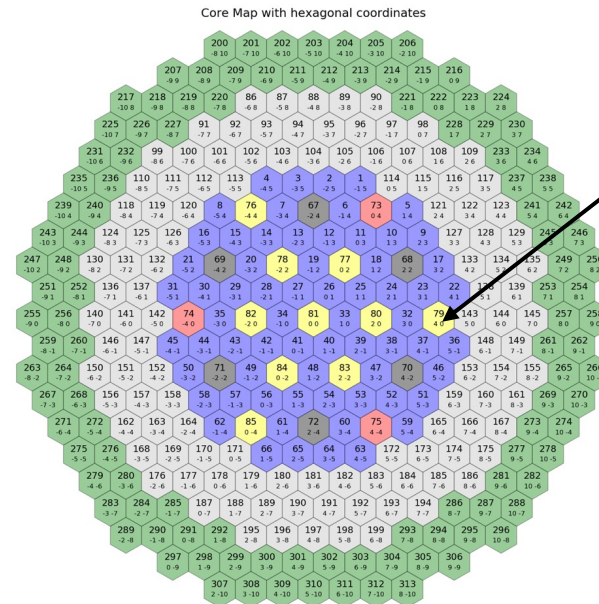




ELTA-CL Design Process – Purpose and Requirements

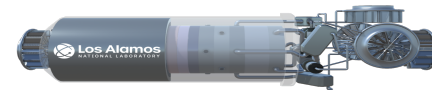


- What is the ELTA-CL?
- ELTA-CL purpose
 - Westinghouse reactor concept
- Desired information
 - Irradiated structural material erosion/corrosion
 - Fuel performance behavior under expected irradiated conditions
 - Irradiated material characteristics (irradiation growth, swelling, embrittlement)
- Requirements include
 - Target fuel linear heat generation rate (LHGR)
 - Bounding fast flux
 - Peak coolant temperature and velocity conditions & many more!
- The ELTA-CL design process aims to fulfill all requirements within the VTR core environment with no interference on the VTR core operation

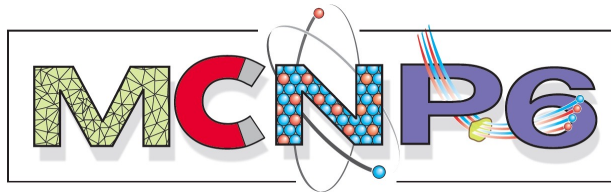




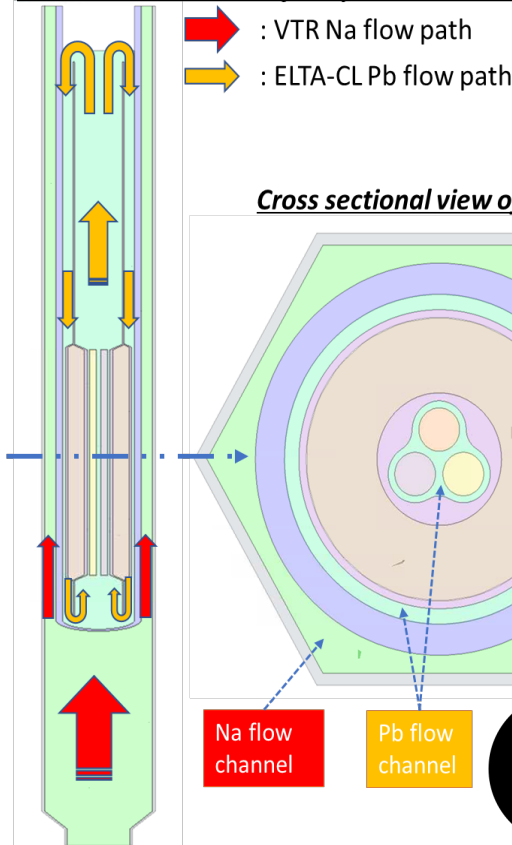
ELTA-CL Design Process



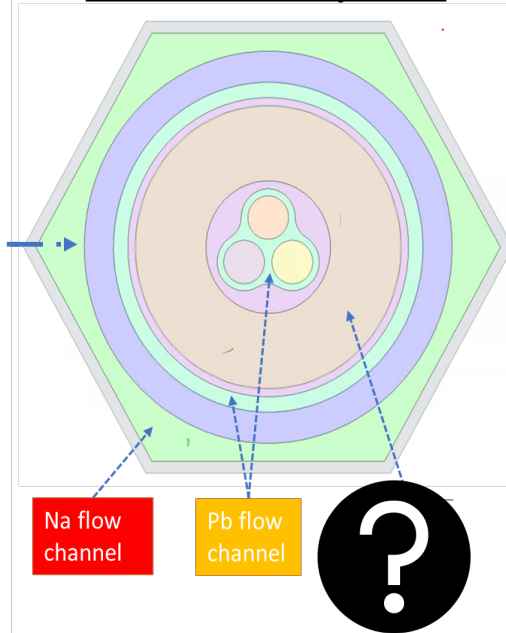
- Key design features:
 - Fueled rods (fissile) in the cartridge
 - Lead coolant flowing within the cartridge
 - VTR sodium heat sink
- Self-contained flow loop and heat generation
 - Multiple barriers
- The cartridge aims to satisfy regulatory (NRC) rigor
 - Generate experimental data
 - Validate models
 - Domains of safe operation
- What's the “?”



Axial view with Na/Pb flow paths in ELTA-CL design

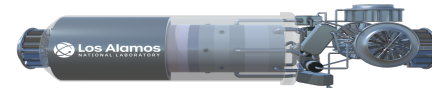


Cross sectional view of ELTA-CL

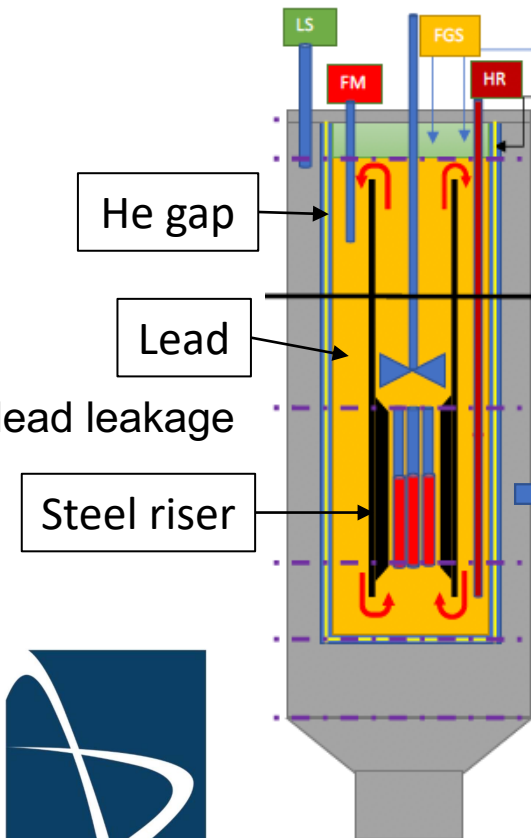
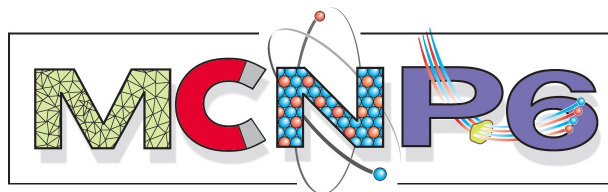


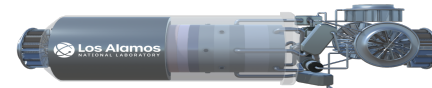


ELTA-CL Design Process – Baseline Design



- ELTA-CL baseline design
 - Thin He gap
 - Large lead volume
 - Solid steel riser
 - Preliminary calculations looked good
- Features included
 - He gap serving as the filler between safety barriers preventing lead leakage into the sodium core coolant
 - Simple design
- Problem: Unexpectedly high gamma heating
 - Must answer:
 - How high?
 - How to mitigate?





ELTA-CL Design Process – Baseline Design

- Utilize the high-fidelity MCNP model
- Model the ELTA-CL at internal and peripheral locations
- Gamma heating
 - 75-80% of heat deposition irrespective of position
 - Magnitude of heat deposition is position dependent
- Cartridge heating values are excessively high
 - Design modifications are a must

MCNP simulations of the VTR core highlighted that we needed to make significant design changes to accommodate the photon environment

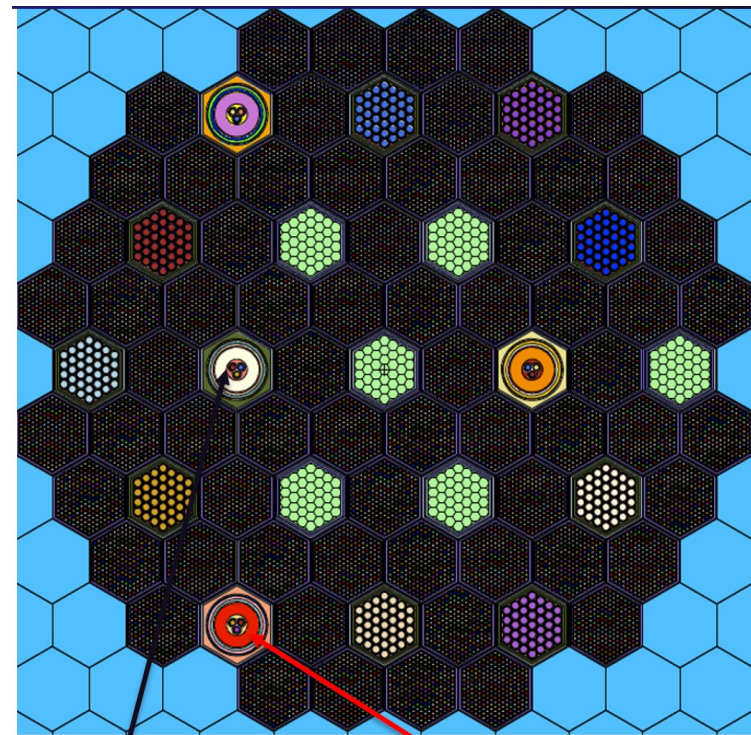
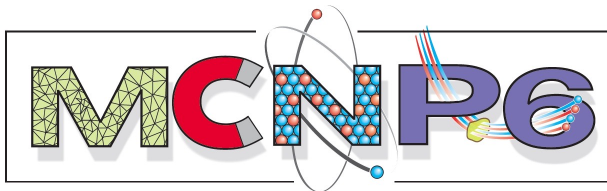
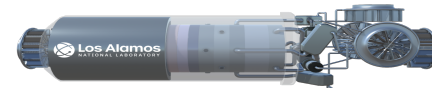


Figure 2 Experimental cartridge radial geometry

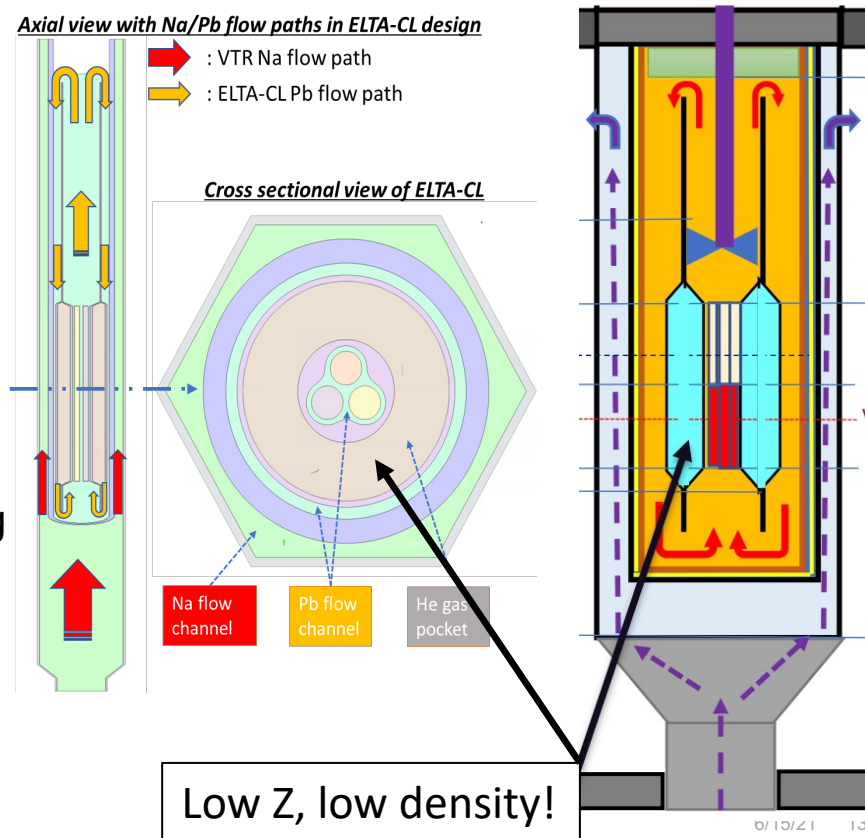
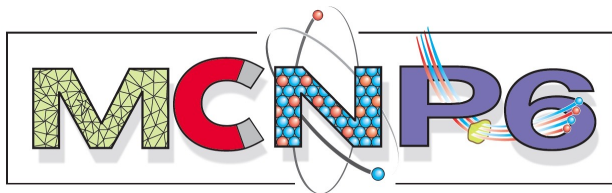
Internal (82) vs **Peripheral (85)**



ELTA-CL Design Process – Modified Design



- **?** Revisited!
- Must lower lead temperature by:
 - Increasing heat transfer
 - Lowering heat (photon) deposition
- He safety gap changes
- Riser design modifications
 - Convective heat transfer
 - Expand the riser in the active core region
 - Lower high Z atom density, lower photon heating



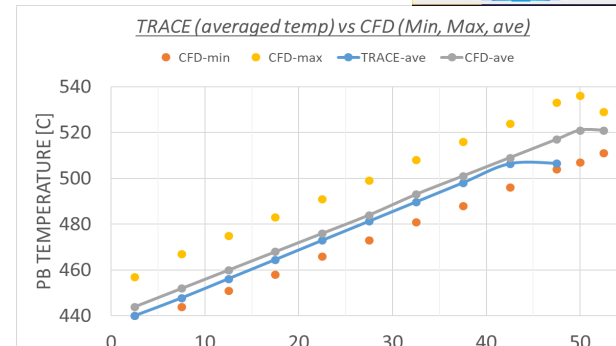
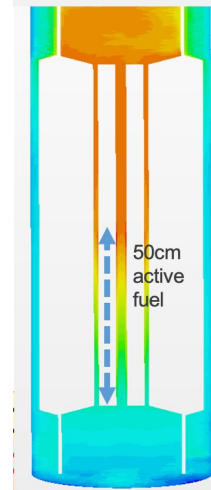
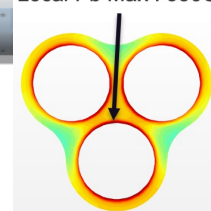


ELTA-CL Design Process – Modified Design

- The modified design sufficiently reduced photon heating
 - Only in the peripheral position
 - **Determination: internal position has too high of a photon flux for a heavy metal cartridge**
- Preliminary thermal calculations were simplified 1-D
 - Higher fidelity thermal modeling needed, thus CFD
- Simulate temperature response in 3-D
 - Determine radial temperature profile, compare to 1-D
 - The max CFD temperature ~20 C higher
- High fidelity multi-physics simulations informed that the local max temperature is above the design target
 - More design work needed



Local Pb Max : 536C

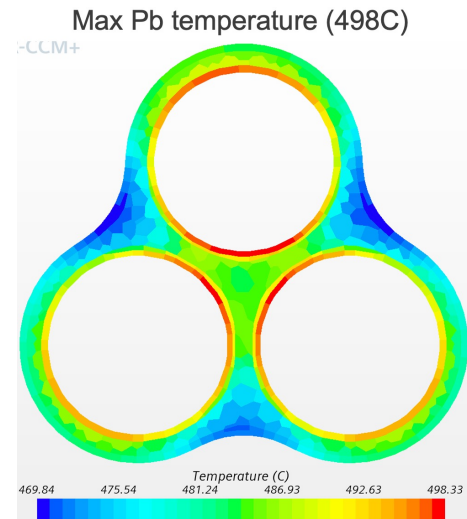
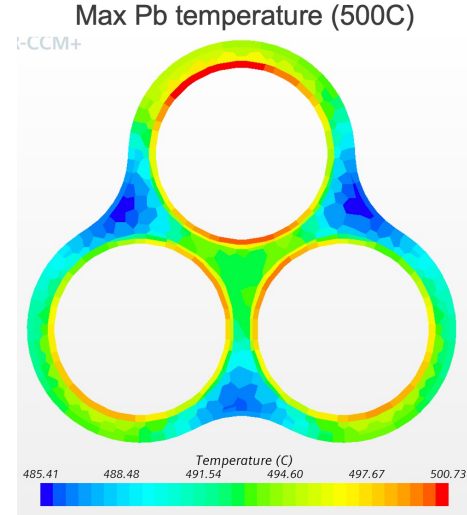
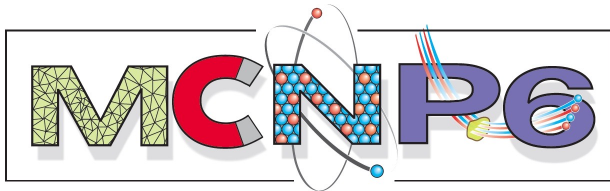




ELTA-CL Design Process – “More” Modified Design

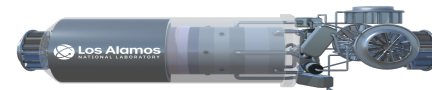
- Design changes “to date”
 - Adjust safety barrier fill, riser design, peripheral location
 - Still above design target by $\sim 30^{\circ}\text{C}$
- Next step, iterate on CFD simulations
 - Increase sodium flow rate (minimally effective)
 - Investigate axial enrichment variation in the fuel (top)
 - Increase “He pocket” within manufacturable tolerances (bottom)
- Successfully reduced max clad temperature to design target

Utilizing combined MCNP+CFD simulations, two viable design options have been determined

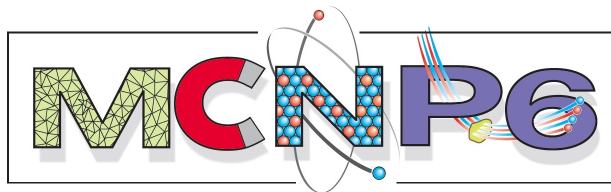
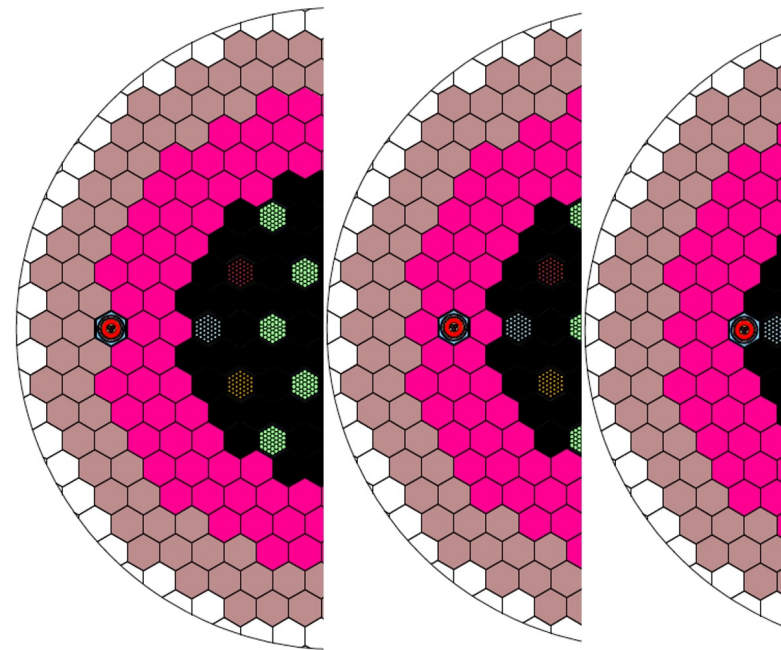




ELTA-CL Design Process – Connection with Collaborators

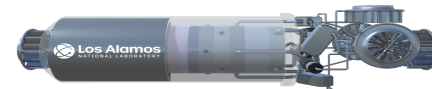


- Design process required frequent collaboration
 - UNM Pb corrosion tests (LOBO loop)
 - Westinghouse specifies design requirements
 - Westinghouse, LANL colleagues, and ORNL collaborate on instrumentation designs
- MCNP simulations inform
 - Westinghouse instrumentation
 - Alternate cartridge design team photon heating constraints
- Characterization of cartridge behavior at alternate locations
 - Multiple reflector locations (right)
 - Cartridge placement dependent on design objectives





ELTA-CL Design Process – Conclusions



- MCNP based photon heating calculations have been invaluable
- Instrumentation design informed by neutron spectrum and flux (neutron and photon) intensities
- Non-fueled ELTA-CL design decisions have been accelerated
- Collaborations include aiding in the design of the ELTA-CG ("cartridge gas"),
 - INL & General Atomics material power depositions provided for rapid design iterations

High fidelity multi-physics simulations in particle transport (MCNP), and fluid flow (CFD) have been utilized in concert to rapidly mature the ELTA-CL design, and aid collaborators across numerous institutions

